

The Downshift of Electron Plasma Oscillations in the Electron Foreshock Region

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Electron plasma oscillations in the earth's electron foreshock region are observed to shift above and below the local electron plasma frequency. As plasma oscillations shift downward from the plasma frequency, their bandwidth increases and their wavelength decreases. Observations of plasma oscillations well below the plasma frequency are correlated with times when ISEE 1 is far downstream of the electron foreshock boundary. Although wavelengths of plasma oscillations below the plasma frequency satisfy $k\lambda_{pe} \approx 1$, the Doppler shift due to the motion of the solar wind is not sufficient to produce the observed frequency shifts. A beam-plasma interaction with beam velocities on the order of the electron thermal velocity is suggested as an explanation for plasma oscillations above and below the plasma frequency. Frequency, bandwidth, and wavelength changes predicted from the beam-plasma interaction are in good agreement with the observed characteristics of plasma oscillations in the foreshock region.

INTRODUCTION

In this paper, observations of electron plasma oscillations are interpreted using a beam-plasma theory. Electron plasma oscillations upstream of the earth's bow shock were first reported by *Fredricks et al.* [1968]; using OGO 5 spacecraft data, they reported enhanced electric field intensities near the local electron plasma frequency. Also using OGO 5 spacecraft data, *Scarf et al.* [1971] identified electric field enhancements near the local plasma frequency and associated these enhancements with electrons streaming into the solar wind from the bow shock. The waves were identified by Scarf et al. as either electron plasma oscillations or upper hybrid waves. Later, *Fredricks et al.* [1971] demonstrated that observations of electric field enhancements near the plasma frequency were consistent with the interpretation that the waves were electron plasma oscillations generated by a beam-plasma interaction. The electrostatic nature of the waves was confirmed by *Rodriguez and Gurnett* [1975] using simultaneous electric and magnetic field measurements from IMP 6.

Following the observations of the emissions at the plasma frequency, their polarization and wavelength were measured by several investigators. The polarization of the oscillations was measured from IMP 6 data by *Rodriguez and Gurnett* [1975, 1976] and was found to be primarily along the magnetic field. This measurement confirmed the identification of the waves as electron plasma oscillations and eliminated the possibility that they are upper hybrid waves. The wavelength of the plasma oscillations was estimated to be several kilometers by *Gurnett and Frank* [1975]. These wavelength estimates were confirmed by *Gurnett et al.* [1979] and *Anderson et al.* [1981], using ISEE 1 and 2 electric field data.

Filbert and Kellogg [1979] were the first to consider the detailed origin of the electron beams responsible for the plasma oscillations. They analyzed the effect of the motion of the solar wind on electrons streaming from the bow shock. Electrons streaming from the bow shock are convected down-

stream due to the $\mathbf{v} \times \mathbf{B}$ electric field of the solar wind. As is illustrated in Figure 1, high-energy electrons originating from the tangent point define a boundary called the electron foreshock boundary. Upstream of this boundary, no electrons streaming from the bow shock are observed. The region downstream of the foreshock boundary and upstream of the bow shock is called the electron foreshock region. *Filbert and Kellogg* noted that electrons streaming into the solar wind from the bow shock with velocities below a certain critical velocity can not reach the spacecraft. The magnitude of the critical velocity depends on the location of the spacecraft in the foreshock region. In the foreshock region the reduced one dimensional electron distribution in the plasma rest frame has a positive slope at the critical velocity. This reduced electron distribution is called a time-of-flight distribution. *Filbert and Kellogg* considered a model time-of-flight distribution with the critical velocity much greater than the electron thermal velocity and demonstrated that plasma oscillations can be generated near the electron plasma frequency. This model is valid for times when the spacecraft is located near the foreshock boundary. Intense electrostatic emissions at the plasma frequency were reported by *Filbert and Kellogg* coincident with foreshock boundary crossings. They suggested that high-energy electron beams, of the type first reported by *Anderson* [1968, 1969], should be coincident with foreshock boundary crossings. Thin sheets of high-energy electrons associated with the foreshock boundary were reported by *Anderson et al.* [1979]. Also, reduced distributions associated with the foreshock boundary have been reported by *Fitzenreiter et al.* [1984] which may be unstable to generation of electron plasma oscillations.

Another feature of plasma oscillations in the foreshock region is that they are observed to vary in frequency. Frequency variations of plasma oscillations on the order of a few kilohertz were reported by *Fredricks et al.* [1972]. These frequency variations were correlated with fluctuations in both the local electron density and the total magnetic field. Based on the magnetic field fluctuations, it was suggested by *Fredricks et al.* that these frequency variations were caused by electron density fluctuations associated with oblique magnetohydrodynamic waves in the foreshock region.

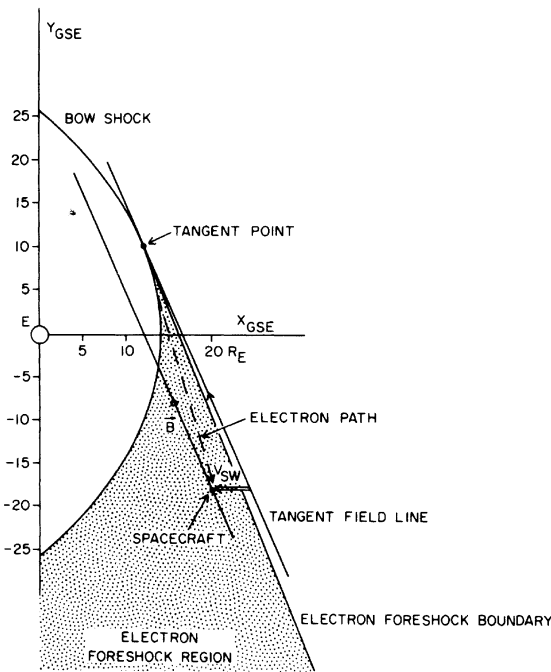


Fig. 1. Electrons streaming from the bow shock are convected downstream due to the motion of the solar wind. Electrons originating from the tangent point with very high energies define a boundary called the electron foreshock boundary. Downstream of this boundary is a region called the electron foreshock region. In this region the "beam" of electrons originating from the bow shock has a characteristic lower cutoff velocity. This cutoff velocity occurs because electrons below a certain critical velocity are convected downstream before they reach the spacecraft.

A different type of frequency variation of the electrostatic emissions in the foreshock region was reported by *Rodriguez and Gurnett* [1975]. The reported observations of electrostatic emissions from 3 kHz to the plasma frequency, which is usually about 30 kHz. It is not clear from their study which electrostatic wave mode was observed below the plasma frequency. The emissions observed could have been a mixture of ion acoustic waves, which range from 0 to 10 kHz, and electron plasma oscillations, which as will be shown, range from near 0 kHz to about 30 kHz. It was suggested by *Rodriguez and Gurnett* that the emissions below the plasma frequency were plasma oscillations that were strongly Doppler shifted due to the motion of the solar wind. However, their explanation is doubtful because if the wavelength at the plasma frequency is several kilometers, as was estimated by *Gurnett and Frank* [1975], then the Doppler shift due to the motion of the solar wind is less than 1 kHz.

Recently, *Etcheto and Faucheux* [1984] made a detailed study of the plasma oscillations below the plasma frequency using data from the relaxation sounder [*Harvey et al.*, 1978] on ISEE 1. They reported plasma oscillations not only below the plasma frequency, but also slightly above the plasma frequency. The plasma oscillations below the plasma frequency were reported to have large bandwidths ($\Delta f/f \approx 0.3$) and long wavelengths ($\lambda \gg \lambda_{De}$). The observations of plasma oscillations below the plasma frequency were also found to be correlated with times where ISEE 1 was far downstream of the foreshock boundary. The mechanism for generation of plasma oscillations below the plasma frequency was not identified.

The purpose of this paper is (1) to report high-time resolu-

tion observations of plasma oscillations at, above, and below the plasma frequency, (2) to discuss the characteristics of the plasma oscillations, and (3) to propose a mechanism for explaining the shift in the frequency of the oscillations away from the plasma frequency. High-resolution spectrograms from the University of Iowa wideband receiver on ISEE 1 are used to study the complex temporal and frequency structure of the plasma oscillations below the plasma frequency. Some of the characteristics are found to differ from those reported by *Etcheto and Faucheux* [1984]. Predictions from the proposed mechanism are found to agree with the observed frequency shift, bandwidth, and wavelength presented in this paper.

Plasma wave data from the University of Iowa plasma wave instruments on ISEE 1 and 2 are used in this study. A description of the plasma wave instruments is given by *Gurnett et al.* [1978]. Density, solar wind velocity, and temperature values in this study are a result of moment calculations of three-dimensional distributions measured by the Goddard Space Flight Center electron spectrometer on ISEE 1. For information on the Goddard Space Flight Center electron spectrometer, see *Ogilvie et al.* [1978]. In addition to moments of the electron distribution, the time evolution of the reduced one-dimensional electron distribution $F(v_{\parallel})$ is used in this study.

OBSERVATIONS OF PLASMA OSCILLATIONS

Electron plasma oscillations in the electron foreshock region occur at the local plasma frequency, and in some cases may shift slightly above or substantially below the plasma frequency. Plasma oscillations are observed at frequencies ranging from less than $0.1 f_{pe}$ to about $1.1 f_{pe}$, where f_{pe} is the local electron plasma frequency ($f_{pe} = 9000(n_0)^{1/2}$ Hz). For the foreshock region this frequency range is from about 3–30 kHz. A typical example of plasma oscillations that are shifted substantially from the plasma frequency is illustrated in Figure 2. The top panel of Figure 2 is a wideband frequency-time spectrogram from the ISEE 1 wideband receiver which was taken when the spacecraft was located in the foreshock region. In the bottom panel of Figure 2 the plasma frequency was calculated from the equation $f_{pe} = 9000(n_0)^{1/2}$, where n_0 is the electron density in units of cm^{-3} , and the frequency is in hertz. During the time interval from 0633:00 to 0633:30 UT, the plasma oscillations are seen to vary from f_{pe} to about $0.25 f_{pe}$.

The complex nature of the plasma oscillations illustrated in Figure 2 is due to the presence of MHD waves associated with ions streaming from the bow shock [*Scarf et al.*, 1970]. The presence of MHD waves is inferred from the fluctuations in the electron density. The presence of the ions streaming from the bow shock is inferred from the presence of ion acoustic waves in the 0–10 kHz range. The effects of the MHD waves on the frequency spectrum is not considered in this study because, as will be shown, the downshifts of plasma oscillations also occur when the MHD waves and upstreaming ions are not present.

Another characteristic of plasma oscillations, which was discussed by *Etcheto and Faucheux* [1984], is illustrated in Figure 2. At 0638:40 UT the plasma oscillations appear as a narrow-band emission near the plasma frequency. From 0638:40 to 0639 UT, the plasma oscillations shift downward from the plasma frequency. Coincident with this shift the bandwidth of the emissions increases from a few hundred hertz to about ± 2 kHz. From the study of numerous events such as those illustrated in Figure 2 it was found that an

ISEE-1 WIDEBAND DATA
 OCTOBER 31, 1977 DAY 304
 R = 22 R_E LOCAL TIME = 11 HRS

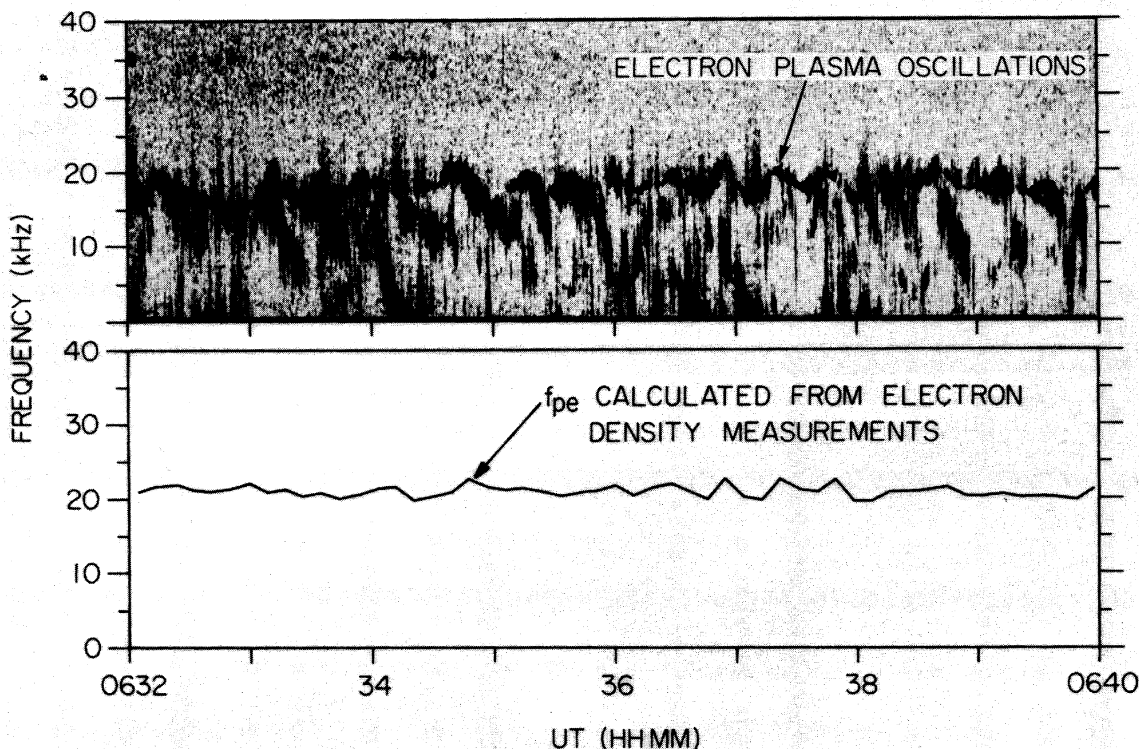


Fig. 2. The top panel is a frequency-time wide-band spectrogram from the ISEE 1 side-band receiver taken when the spacecraft was located in the foreshock region. The bottom panel is a plot of the plasma frequency determined from electron density measurements. From 0633 to 0633:30 UT and from 0638:30 to 0639 UT, plasma oscillations are observed to shift well below the plasma frequency. Coincident with these shifts is an increase in the bandwidth of the emissions from a few hundred hertz at the plasma frequency to ± 2 kHz well below the plasma frequency.

increase in the bandwidth of plasma oscillations always accompanies a large shift in the frequency away from the plasma frequency.

In addition to the change in the bandwidth, the wavelength of plasma oscillations below the plasma frequency also changes. The wavelength of electrostatic emissions such as plasma oscillations can be inferred by comparing spectral density measurements obtained from two different length electric antennas. To obtain the wavelengths of plasma oscillations at the plasma frequency, Gurnett *et al.* [1979] compared spectral density measurements from a 215-m dipole antenna on ISEE 1 to measurements from a 30-m dipole antenna on ISEE 2. It was found that spectral density measurements at the plasma frequency from the two antenna agreed within 10%. Gurnett *et al.* concluded that plasma oscillations at the plasma frequency have wavelengths longer than the antenna on ISEE 1. A typical electron Debye length in the foreshock region is 9 m, so plasma oscillations at the plasma frequency satisfy the relation $k\lambda_{De} \ll 1$. The long wavelengths of plasma oscillations observed at the plasma frequency were also verified by Anderson *et al.* [1981] using the same method.

In this study, electric field spectrums obtained from ISEE 1 plasma wave data are compared to ISEE 2 for times when plasma oscillations are observed to shift well below the

plasma frequency. Spectrums from over 15 hours of data containing downshift events were compared. An example of this comparison is illustrated in Figure 3. The electric field spectrums were averaged over 20 min to obtain the graph illustrated in Figure 3. The time interval in Figure 3 contained numerous downshift events similar to those illustrated in Figure 2. During the 20-min interval the spacecraft were 30 km apart and both spacecraft were moving at about 1 km/s. The long averaging time and the close proximity of ISEE 1 to ISEE 2 were chosen to reduce the effect of temporal and spatial variability of the spectral density. For frequencies between 10 and 20 kHz, the spectral densities measured by ISEE 2 are greater than those measured by ISEE 1 by about a factor of 5. At the local plasma frequency (30 kHz) the spectral density measurements from the two spacecraft differ by less than 10%. The difference in the measured spectral densities for frequencies between 10 and 20 kHz is interpreted as an indication that the wavelengths of plasma oscillations below the plasma frequency are between 30 and 215 m. Since a typical Debye length for the foreshock region is about 9 m, wavelengths between 30 and 215 m satisfy $k\lambda_{De} \approx 1$. As a result of the study of numerous spectral density comparisons similar to the one illustrated in Figure 3, it is concluded that when the frequency is shifted well below the plasma frequency, plasma

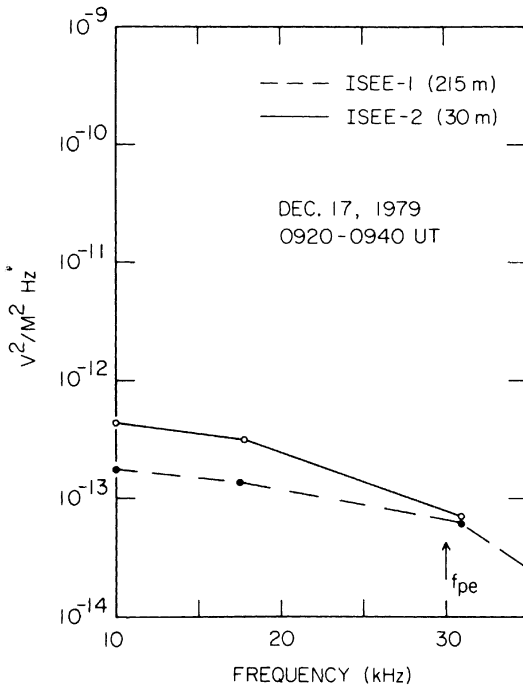


Fig. 3. A plot of a 20-min average spectral density versus frequency for an event when plasma oscillations occurred well below the plasma frequency. The plasma frequency for this event was about 30 kHz. For frequencies between 10 and 20 kHz, the spectral density from ISEE 2 is greater than that from ISEE 1 by about a factor of 5. This difference indicates that the wave lengths of the plasma oscillations well below the plasma frequency are shorter than the ISEE 1 antenna (215 m) and longer than the ISEE 2 antenna (30 m).

oscillations have short wavelengths, $\lambda \approx 2\pi\lambda_{De}$, and when the frequency is at the plasma frequency, plasma oscillations have long wavelengths, $\lambda \gg \lambda_{De}$. The wavelength is assumed to decrease in a continuous manner because plasma oscillations shift in a continuous manner from the plasma frequency to well below the plasma frequency.

In contrast to the report in this paper of short wavelengths below the plasma frequency, *Etcheto and Faucheux* [1984] report long wavelengths below the plasma frequency. *Etcheto and Faucheux* found no difference in the spectral density measurements from the 215-m-long wire dipole antenna on ISEE 1 and the 130-m sphere-to-sphere antenna also on ISEE 1. The small difference in the effective lengths of the two antennas (at best a factor of 2) may account for the fact that no difference in the two spectral density measurements was observed. In contrast, the difference in the spectral density measurements in Figure 3 of this paper is distinguishable because the effective lengths of the two dipole antennas used in the comparison differ by about a factor of 7. Thus the smaller difference in the effective lengths of the two antennas used by *Etcheto and Faucheux* may account for the fact that no difference in the spectral density measurements below the plasma frequency was observed and thus it was concluded that the wavelengths were long.

Although plasma oscillations below the plasma frequency are reported in this paper to have short wavelengths, the observed shifts from the plasma frequency can not be attributed entirely to Doppler shifts. Consider, for example, the event illustrated in Figure 2. On October 31, 1977, at 0633 UT, the solar wind velocity was 335 km/s, the number density was 5 cm^{-3} , and the electron temperature was $1.1 \times 10^5 \text{ K}$. As-

suming plasma oscillations with a minimum wavelength of $2\pi\lambda_{De}$, the maximum Doppler shift is estimated to be 5 kHz. The maximum Doppler shift is only about 50% of the observed shift from the plasma frequency in Figure 2. For example, at 0638:50 UT, plasma oscillations are observed to $0.33 f_{pe}$, but plasma oscillations Doppler shifted from the plasma frequency would occur at or about $0.7 f_{pe}$.

A study was performed to determine the change in the characteristics of both the wave and particle data as ISEE 1 penetrates deeper into the foreshock region. This study was similar to that of *Etcheto and Faucheux* [1984]. The three-dimensional model of the bow shock used in the study is discussed by *Filbert and Kellogg* [1979]. The equation for the bow shock is

$$X = 14.6 - 0.0223(Y^2 + Z^2) \quad (1)$$

where X , Y , and Z are the geocentric solar ecliptic (GSE) coordinates of the bow shock in units of earth radii. ISEE 1 data pool values for spacecraft coordinates and magnetic field components were used. The solar wind flow velocity was assumed to be in the $-X_{GSE}$ direction. If the magnetic field was found to intersect the bow shock, then the distance along the solar wind velocity from the tangent field line to the spacecraft field line was computed. This distance is an indication of the depth of penetration of the spacecraft into the foreshock region. The simple bow shock model and 64-s average magnetic field data is adequate for the study because large uncertainties in the shape and location of the bow shock and rapid changes in the magnetic field geometry allows only a qualitative discussion of the spacecraft location. In this study, 25 hours of wide-band data containing over 150 foreshock boundary crossings were used. These events covered a wide range of magnetic field geometries and spacecraft locations.

The characteristics of plasma oscillations were found to depend on the depth of penetration of the spacecraft into the foreshock region. An example of the change in characteristics of plasma oscillations is illustrated in the middle and bottom panels of Figure 4. The middle panel of Figure 4 is a frequency-time spectrogram from ISEE 1. In the middle panel the narrow-band emissions at 18 kHz are electron plasma oscillations. The bottom panel is a plot of Diff, the distance from the spacecraft to the tangent field line along the solar wind velocity direction. A large negative value of Diff implies that the spacecraft is far downstream of the foreshock boundary. A positive value of Diff implies that the spacecraft is on a field line not connected to the bow shock. From 1237 to 1238 UT the spacecraft moves from the foreshock boundary to a few R_E downstream of the foreshock boundary and plasma oscillations shift from the plasma frequency to slightly above the plasma frequency. From 1238 to 1240:30 UT the spacecraft moves from a few R_E downstream of the foreshock boundary to far downstream of the foreshock boundary. Coincident with this movement, plasma oscillations shift from slightly above the plasma frequency to well below the plasma frequency. From 1241:30 to 1242:30 UT the spacecraft moves from far downstream of the foreshock boundary to just upstream of the foreshock boundary. Coincident with this movement, plasma oscillations shift first from well below the plasma frequency to slightly above the plasma frequency, then from slightly above the plasma frequency to the plasma frequency.

There is a considerable difference between the spectrum in the middle panel of Figure 4 and the spectrum in Figure 2. The reason for this difference is that ISEE 1 is upstream of the ion foreshock boundary during the event illustrated in Figure

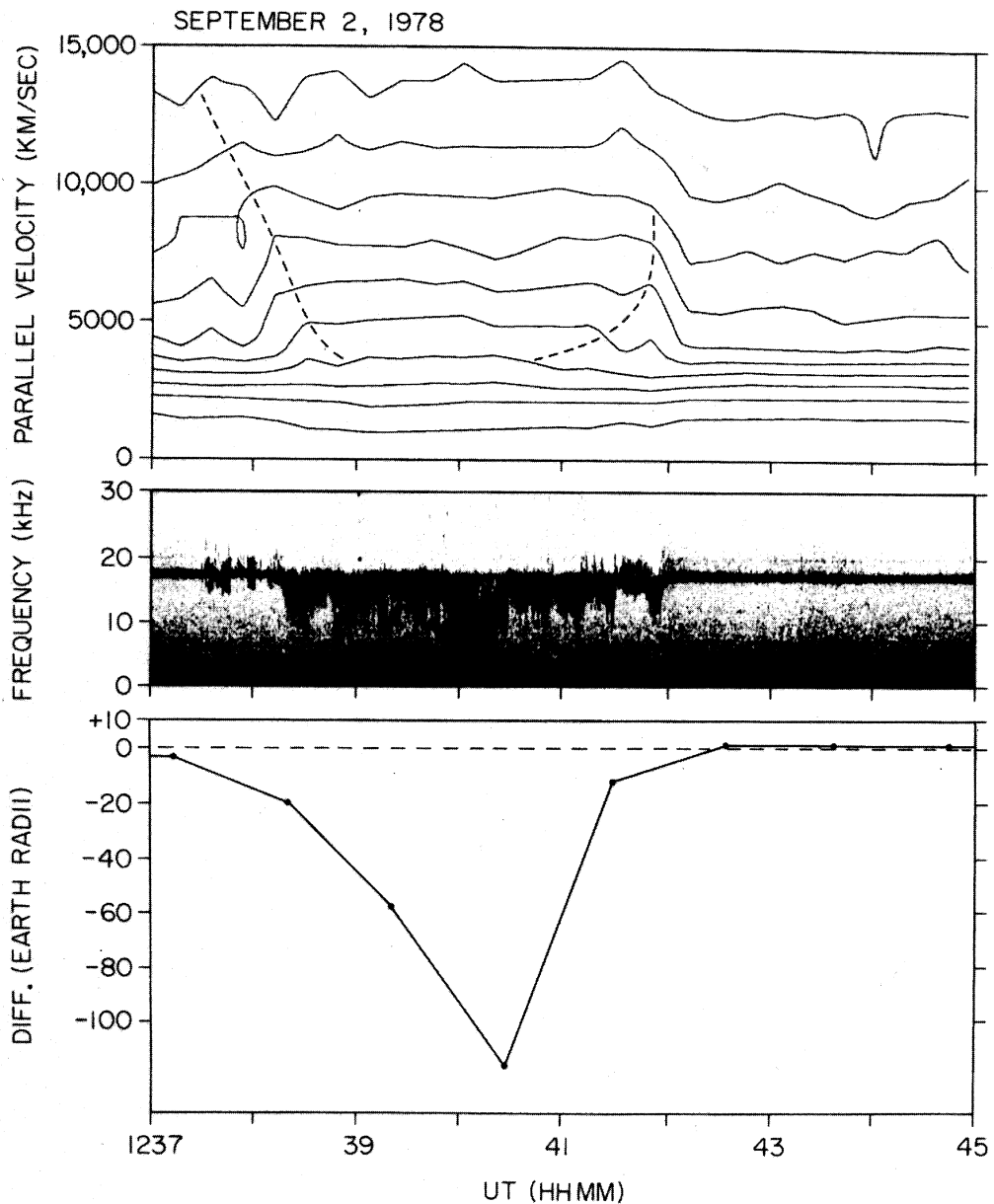


Fig. 4. The top panel is a plot of isocontours of $-\ln(F(v_{\parallel}))$ for electrons streaming from the bow shock. A shift of a contour from low to high velocities is an indication of an increase in the flux of electrons at low velocities. The middle panel is a frequency-time spectrogram. The narrow-band emissions at 18 kHz are electron plasma oscillations. The bottom panel is a plot of Diff. A large negative value of Diff implies that ISEE 1 is far downstream of the foreshock boundary. From 1237 to 1239 UT, ISEE 1 penetrates deeply into the foreshock region, the flux of electrons streaming from the bow shock increases at successively lower velocities, and plasma oscillations shift first above, then below the plasma frequency. The reverse happens from 1240 to 1242 UT.

4 and is downstream of the ion foreshock boundary during the event illustrated in Figure 2. The lack of ion acoustic waves in the 0–10 kHz range in the spectrogram in Figure 4 is an indication that there are no upstreaming ions present. (The dark band in the 0–10 kHz range is an artifact of the processing of the wide-band data and is not ion acoustic waves.) Because downshifts of plasma oscillations occur when no upstreaming ions are present, it is concluded that the downshifts are not generated by presence of ion beams.

The difference in the spectrograms illustrated in Figures 2 and 4 would be difficult to distinguish using a sounding instrument such as that used in the study by *Etcheto and Fau-*

cheux [1984]. The reason for this difficulty is that the sweep time for the sounder (16 s for 0–50 kHz) is slow enough that discrete features, such as those illustrated in Figure 2, would not appear in the spectrogram. The result would be that one would almost always observe a spectra similar to that in the middle panel of Figure 4. Thus using the high time resolution wide-band data, a fourth classification of plasma oscillations in the foreshock region is identified. The first three classifications of plasma oscillations in the foreshock region were identified by *Etcheto and Faucheux* [1984] as narrow-band emissions at the plasma frequency, broadband emissions slightly above the plasma frequency, and broadband emissions

below the plasma frequency. The fourth classification, illustrated in Figure 2, is identifiable by complex discrete fluctuations of plasma oscillations and is associated with times when the spacecraft is downstream of both the electron and the ion foreshock boundary. These classifications are somewhat arbitrary because plasma oscillations change continuously from one to the other as the spacecraft moves from near the electron foreshock boundary to far downstream of the foreshock boundary.

The change in the characteristics of plasma oscillations is not only associated with deeper penetration into the foreshock region, but is also associated with changes in the electron spectra. Comparison of wave data and electron data from the Godard Space Flight Center electron spectrometer for over 50 foreshock boundary crossings was made. The electron spectrometer was chosen for this study because this instrument can detect the electrons responsible for generation of plasma oscillations and reduced one-dimensional distributions can be generated from the electron data.

A good correlation was observed between the shift of plasma oscillations from the plasma frequency and the increase in the flux of energetic electrons at successively lower velocities. One example of this correlation is illustrated in the top and middle panels of Figure 4. The top panel of Figure 4 is a plot of isocontours of constant $-\ln(F(v_{\parallel}))$ for electrons propagating upstream from the bow shock. Here $F(v_{\parallel})$ is defined as the reduced distribution function. Each contour represents a change of a factor of $\ln(e)$. The phase space density decreases with increasing velocity. The electron thermal velocity is about 1500 km/s. A shift of a contour from low to high parallel velocities is an indication of an increase in the flux of electrons. For example, from 1237 to 1238 UT the contour at 10,000 km/s shifts to about 12,000 km/s, indicating an increase in the flux of electrons with velocities equal to 10,000 km/s.

From 1237:15 to 1239 UT, Diff changes from about $-5 R_E$ to $-60 R_E$, indicating that the location of ISEE 1 in the foreshock region changes from near the foreshock boundary to far downstream of the foreshock boundary. Coincident with the change of location in the foreshock region, plasma oscillations shift upward to about $1.1 f_{pe}$, and then downward to about $0.7 f_{pe}$. As the plasma oscillations shift downward in frequency, the flux of energetic electrons arriving from the bow shock increases at successively lower velocities from 1237:15 to 1239 UT. This trend is illustrated by the first dashed line in the top panel of Figure 4. From 1240:30 to 1242 UT, Diff changes from about $-120 R_E$ to $-5 R_E$, indicating that the location of ISEE 1 in the foreshock region changes from far downstream of the foreshock boundary to near the foreshock boundary. The change in the location is accompanied by a shift of the frequency of plasma oscillations from about $0.6 f_{pe}$ to $1.0 f_{pe}$. The change in the location is also accompanied by a decrease in the flux of energetic electrons at successively higher velocities, as is illustrated by the second dashed line in the top panel of Figure 4. From 1242 to 1244 UT, ISEE 1 is on a magnetic field line which may not be connected to the bow shock. There is no evidence of electrons from the bow shock with velocities less than 30,000 km/s in the electron data. The emissions observed at the plasma frequency from 1242 to 1244 UT may be generated by electrons from the bow shock with velocities greater than 30,000 km/s or may be enhanced thermal emissions [Hoang *et al.*, 1980]. The intensity of these emissions is four orders of magnitude lower than plasma oscillations that are associated with electrons from the bow shock at 1241 UT. There is no change in the apparent

intensity of the emissions in the frequency-time spectrogram because of an automatic gain control on the wideband receiver.

The correlation between the increase in flux of energetic electrons at successively lower velocities and the deeper penetration of the spacecraft into the foreshock region may be an indication that the time-of-flight mechanism discussed by Filbert and Kellogg has an effect on the electron distribution from velocities much greater than the electron thermal velocity to velocities on the order of the electron thermal velocity. This effect is illustrated in Figure 5. When ISEE 1 is far downstream of the foreshock boundary (Figure 5, case 1), the critical velocity may be on the order of the electron thermal velocity. When ISEE 1 is near the foreshock boundary (Figure 5, case 2), the critical velocity is much greater than the electron thermal velocity.

A study of the electron data for several foreshock boundary crossings was made to determine if unstable distributions of the type reported by Fitzenreiter *et al.* [1984] are observed throughout the foreshock region. Reduced one-dimensional distributions that may be unstable to generation of plasma oscillations were found for times when ISEE 1 was located near the foreshock boundary. As the spacecraft penetrated deeper into the foreshock region, the reduced distribution was observed to evolve from a double-peaked distribution to a single-peaked distribution. An example of the time evolution of a reduced distribution is illustrated in Figure 6. The top part of Figure 6 shows three reduced distributions generated from data taken over 3-s intervals spaced 18 s apart. A reference solar wind distribution observed where the spacecraft was not connected to the bow shock is also shown with three reduced distributions. In the bottom part of Figure 6 a frequency-time spectrogram and a plot of Diff are illustrated. From 1237:16 to 1238:20 UT, Diff changed from $-5.6 R_E$ to $-19.0 R_E$, indicating that ISEE 1 penetrated deeper into the electron foreshock region. Coincident with this time period, at

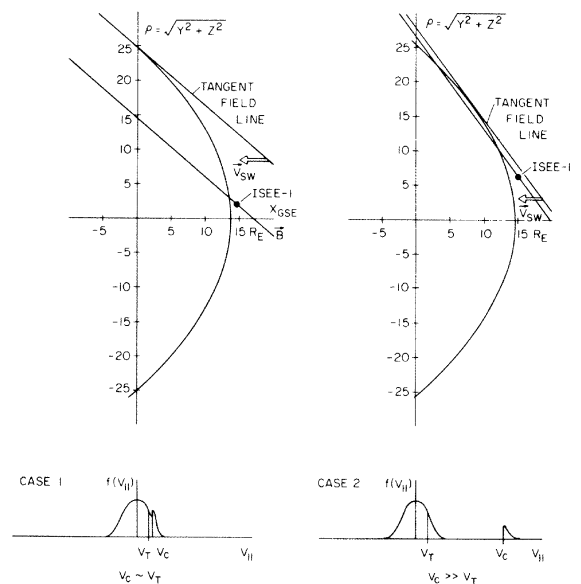


Fig. 5. The reduced one-dimensional distribution depends on the spacecraft location in the foreshock region. When the spacecraft is located far downstream of the foreshock boundary (case 1), the critical velocity is on the order of the electron thermal velocity. When the spacecraft is located near the foreshock boundary, (case 2), the critical velocity is much greater than the electron thermal velocity.

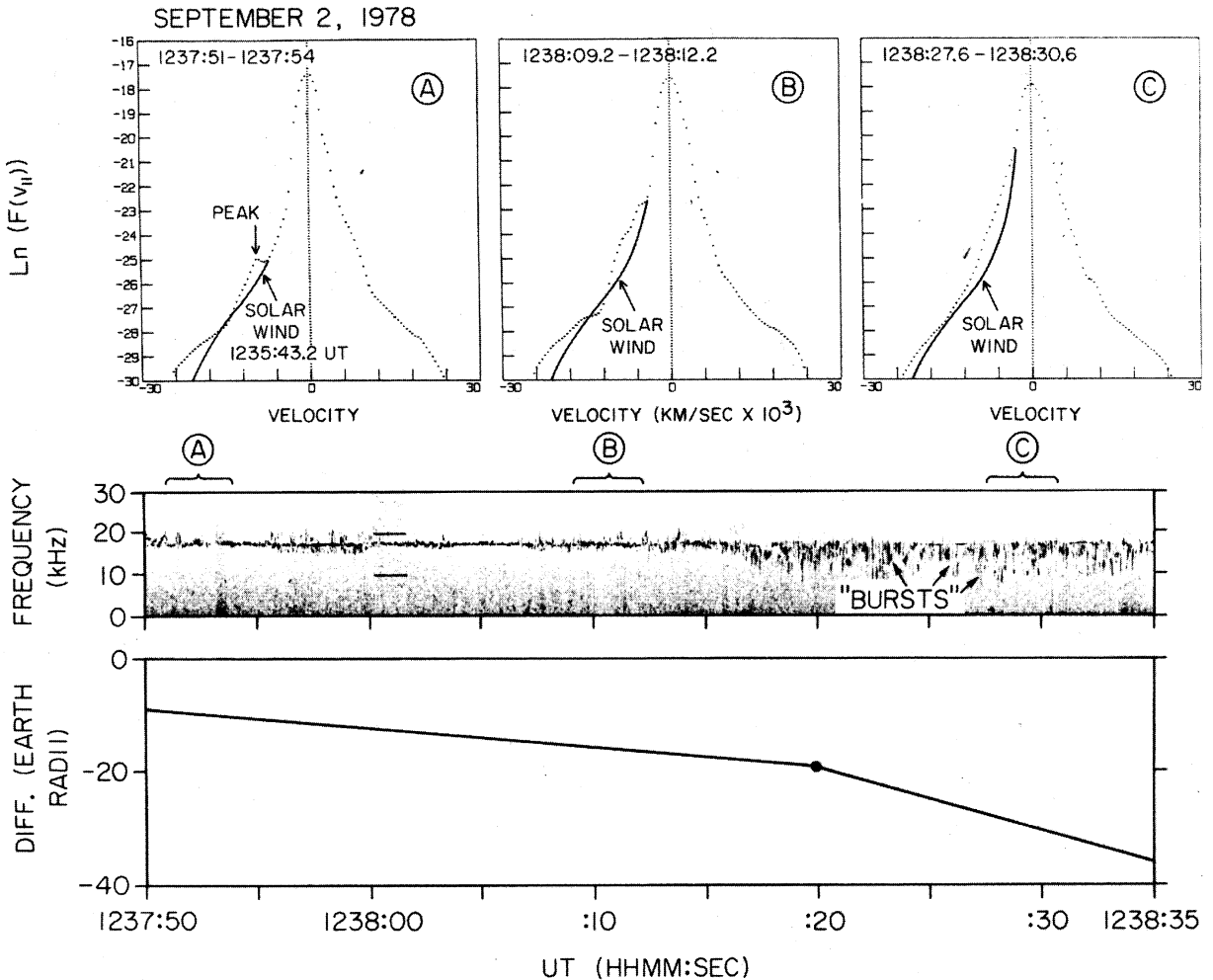


Fig. 6. In the top panels, three reduced one-dimensional distribution obtained from 3 s of data spaced 18 s apart are illustrated. The middle panel is a plot of high resolution wide-band data. The bottom panel is a plot of Diff. At 1237:51-1237:54 UT a second peak is observed in the reduced distribution. At 1238:09.2-1238:12.2 UT a plateau is observed in the reduced distribution. At 1238:27.6-1238:30.6 UT when ISEE 1 is about 25 R_E downstream of the foreshock boundary, no beam is visible in the reduced distribution. One reason why no beam is visible may be that the beam is varying in velocity space much faster than the 3 s used to generate the distribution. Observations of short duration bursts of plasma oscillations at varying frequencies may be evidence of temporal variation of the beam.

1237:51 UT a second peak with a number density of about 10^{-3} to $10^{-4} n_0$, and a parallel velocity of about 9,500 km/s is observed in the reduced distribution. In the second distribution, at 1238:09 UT, a plateau at a parallel velocity of about 6,000 km/s is observed in the reduced distribution. At 1238:27.6 UT, when ISEE 1 is about 25 R_E downstream of the foreshock boundary and plasma oscillations occur below the plasma frequency, there is no second peak or plateau visible in the reduced distribution.

A simulation of another event similar to the one discussed above was made to determine if the electron spectrometer could detect a low-density beam at velocities on the order of the electron thermal velocity. In the simulation the instrument's velocity space sampling was used to sample a model plasma and beam distribution. It was found that a beam with $n_b = 10^{-2}$ to $10^{-3} n_0$ could be detected for any beam velocity, provided that the beam remained at a fixed velocity for the 3 s used to generate a reduced distribution. Reduced distributions can be generated from less than 3 s of data; however, coverage of velocity space is reduced and the chances of detecting beams are diminished.

From the study of wide-band data similar to that shown in Figure 6 there are indications that plasma oscillations below the plasma frequency may be generated by a beam whose velocity varies significantly over a 3-s time period. Inspection of wide-band spectrograms reveals that plasma oscillations below the plasma frequency are time varying emissions spread over a broad range of frequencies. Typically, bursts of less than 50 ms separated by a few tens of milliseconds are observed. The bandwidths of these bursts are usually about 5 kHz. When these bursts are illustrated in a compressed time format as in Figure 4, they appear continuous. When the time scale is expanded as in Figure 6, at 1238:20-1238:35 UT, plasma oscillations below the plasma frequency are bursts of short duration which vary in frequency. It will be shown in the next sections that in the context of linear plasma theory, the temporal and frequency variations of plasma oscillations below the plasma frequency are consistent with the interpretation that plasma oscillations are generated by a beam that varies significantly in velocity on time scales of a few tens of milliseconds. These time scales are much too short to be resolved by any existing electron detector.

Before considering a mechanism for generation of plasma oscillations at somewhat above and much below the plasma frequency, a summary of the basic characteristics of plasma oscillations in the foreshock region is given below.

1. Plasma oscillations are observed at frequencies ranging from less than $0.1 f_{pe}$ to about $1.1 f_{pe}$.

2. As the plasma oscillations shift below the plasma frequency, their bandwidth increases from a few hundred hertz near the plasma frequency to ± 2 kHz well below the plasma frequency.

3. Plasma oscillations at the plasma frequency have wavelengths much greater than a Debye length. Plasma oscillations at frequencies well below the plasma frequency have wavelengths on the order of a few Debye lengths.

4. Plasma oscillations much below the plasma frequency are correlated with times when ISEE 1 is located deep in the foreshock region, far downstream of the foreshock boundary.

5. As the plasma oscillations shift below the plasma frequency, the flux of energetic electrons streaming from the bow shock increases at successively lower velocities.

BEAM-PLASMA THEORY

As was discussed in the introduction, a mechanism for producing unstable electron distribution functions was demonstrated by *Filbert and Kellogg* [1979]. They considered an electron distribution at times when a spacecraft is located near the foreshock boundary. For these times the critical velocity of the beam is much greater than the electron thermal velocity. Downstream of the foreshock boundary the critical velocity of the beam approaches the electron thermal velocity. To obtain solutions of the linear dispersion relation valid for the entire foreshock region, one must consider a beam-plasma interaction without the restriction that the beam velocity be much greater than the electron thermal velocity. *Briggs* [1964], *Reinleitner et al.* [1983], and *Grabbe* [1984] have considered approximations to the linear dispersion relation and have obtained analytical solutions for $\omega(k)$. In this paper a numerical solution to the dispersion relation for a plasma and an electron beam will be presented. Solutions to the dispersion relation are obtained for all beam velocities.

Solution of the linear Vlasov equation yields a dispersion relation of the form

$$D(k, \omega) = 0 = 1 - \sum_s \frac{\omega_{ps}^2}{k^2} \int \frac{\partial F_{os}(v_z)/\partial v_z}{v_z - \frac{\omega}{k}} dv_z \quad (2)$$

where ω_{ps} is the plasma frequency of the s th species, k is the wave number, $F_{os}(v_z)$ is the reduced one dimensional distribution function for the s th species, and ω is the complex frequency.

The electron distribution in the foreshock region is approximated by a Maxwellian distribution

$$F_{oe}(v_z) = \left[\frac{1}{2\pi V_t^2} \right]^{1/2} e^{-[v_z^2/2V_t^2]} \quad (3)$$

where V_t is the electron thermal velocity. The electron distribution in the foreshock is more closely approximated by a bi-Maxwellian [*Feldman et al.*, 1975]. However, the results presented below using a single Maxwellian do not differ greatly from the results obtained using a bi-Maxwellian. The electron beam is approximated by a Lorentzian distribution

$$F_{ob}(v_z) = \frac{C_b}{\pi} \frac{1}{C_b^2 + (v_z - V_b)^2} \quad (4)$$

where C_b is the thermal velocity of the beam, and V_b is the beam velocity. Ions are neglected because the downshifts of plasma oscillations occur when there are no ions observed streaming from the bow shock and because the solar wind ion distribution has a negligible effect on the solutions of dispersion relation.

Substituting (3) and (4) into (2) and integrating one finds

$$D(k, \omega) = 0 = 1 + (k\lambda_{De})^2 + zZ(z) - \frac{n_b/n_0(k\lambda_{De})^2}{(k\lambda_{De}V_b/V_t - ik\lambda_{De}T_b/T_e - \omega/\omega_{pe})^2} \quad (5)$$

where n_b and n_0 are the number density of the beam and the plasma, respectively, T_b and T_e are the temperatures of the beam and the plasma, respectively, $z = \omega/kV_t\sqrt{2}$, and $Z(z)$ is the plasma dispersion function [*Fried and Conte*, 1961].

Equation (5) can be solved for $\omega(k)$ numerically using the Muller method [*Muller*, 1956]. An example of solutions of (5) is illustrated in Figure 7. This illustration shows a graph of ω_i/ω_{pe} versus ω_r/ω_{pe} for $T_b/T_e = 0$, $n_b/n_0 = 0.01$, and $V_b/V_t = 0.5, 1.0, 2.0, 2.5$, and 3.0 where ω_i is the growth rate, and ω_r is the frequency.

For $T_b/T_e \neq 0$, the growth rate for specific values of V_b/V_t is less than the growth rate for $T_b/T_e = 0$. If T_b/T_e is large enough, solutions of the dispersion relation for some values of V_b/V_t are Landau damped. For example, if $T_b/T_e = 0.05$, plasma oscillations are damped for $V_b/V_t < 0.9$, and the maximum growth rate for $V_b/V_t = 1.5$ has decreased by a factor of 3 from the growth rate for $V_b/V_t = 1.5$ and $T_b/T_e = 0$. The reduced growth rate for frequencies below the plasma frequency will not be reflected in the observations if the waves have sufficient time to grow beyond the small amplitude approximation made in the linear Vlasov theory. A nonlinear saturation of the signal would account for the constant spectral density from $0.3 f_{pe}$ to f_{pe} in Figure 3.

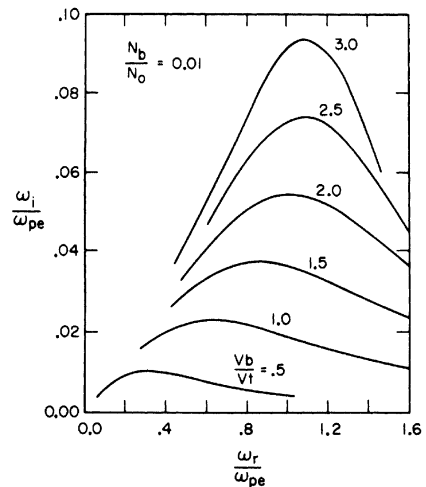


Fig. 7. Solutions to the linear dispersion relation $D(k, \omega) = 0$ are illustrated. The growth rate or imaginary part of the frequency is plotted versus the real part of the frequency. The number density ratio and beam temperature ratio were fixed at 0.01 and 0.0, respectively. Curves representing $\omega(k)$ for various values of V_b/V_t are illustrated. For specific values of V_b/V_t and n_b/n_0 the observed frequency will be the frequency with the maximum growth rate.

For specific values of V_b/V_i , T_b/T_e , and n_b/n_0 , the frequency with the largest growth rate will be the observed frequency. Figure 8 shows the frequency of maximum growth versus V_b/V_i , for $n_b/n_0 = 0.01$ and $T_b/T_e = 0, 0.005, 0.01, 0.05$, and 0.1 . The wave number of maximum growth versus V_b/V_i for the same values of n_b/n_0 and T_b/T_e is illustrated in Figure 9.

The values of n_b/n_0 and T_b/T_e were chosen to approximate conditions in the foreshock region. Typically, density ratios are on the order of 10^{-2} to 10^{-3} . The small temperature ratios were chosen to approximate the steep positive slope of the electron beams. The steep positive slope is due to the time-of-flight mechanism. From Figure 8 one can see that if the beam temperature changes for $T_b/T_e = 0$ to $T_b/T_e = 0.1$, a downshift of plasma oscillations occurs if $0 < V_b/V_i \lesssim 3$. A change in the beam temperature may also occur simultaneously with a change in the beam velocity as the spacecraft penetrates deeper into the foreshock region. An indication of a change in the beam temperature is illustrated in Figure 4. From 1238:30 to 1239:00 UT the contours of the reduced distribution at velocities less than 5000 km/s shift more gradually as ISEE 1 penetrates more deeply into the foreshock region. The more gradual shift in the contours may be an indication that the steep positive slope of the time-of-flight distribution occurs near the foreshock boundary and becomes less steep as ISEE 1 moves into the foreshock region. Such a change in the steepness may increase the downshift of plasma oscillations from the plasma frequency.

Although the above numerical solutions to the linearized Vlasov equation are completely general, it is useful to solve the dispersion relation analytically by considering two limiting forms of (5). By obtaining these solutions, the influence of various parts of the dispersion relation on the frequency of maximum growth can be illustrated. The limiting forms of (5), for slightly different initial conditions, are discussed by Briggs [1964] and Grabbe [1984].

The first limiting form of (5) can be obtained by assuming $V_b/V_i \gg 1$. This limiting form is equivalent to the high phase velocity approximation, $\omega/k \gg V_i$. Using the high phase velocity approximation for the plasma dispersion function (and in the limit of $\omega_i \rightarrow 0$), (5) can be approximated as

$$D(k, \omega) = 0 \approx 1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{3\omega_{pe}^4 (k\lambda_{De})^2}{\omega^4} - \frac{n_b/n_0 (k\lambda_{De})^2}{(k\lambda_{De} V_b/V_i - \omega/\omega_{pe})^2} \quad (6)$$

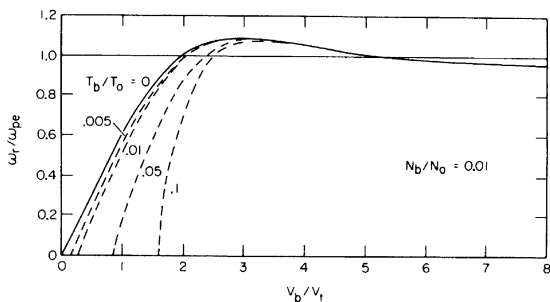


Fig. 8. The frequency of maximum growth determined from solutions of $D(k, \omega) = 0$ is plotted versus V_b/V_i . The number density ratio was fixed at 0.01. Curves for various values of T_b/T_e are illustrated. For $2 < V_b/V_i < 5$, plasma oscillations occur above the plasma frequency. For $V_b/V_i < 2$, plasma oscillations occur below the plasma frequency.

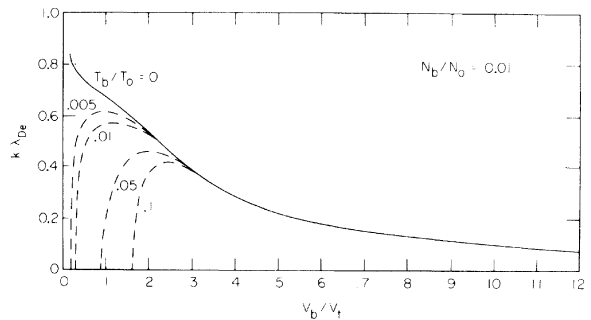


Fig. 9. The wave number of maximum growth is plotted versus V_b/V_i . The number density ratio was fixed at 0.01. As V_b/V_i decreases, wavelengths of plasma oscillations decrease. For $V_b/V_i \lesssim 4.5$ wavelengths of plasma oscillations are less than the 215-m antenna on ISEE 1.

where the additional assumption of a cold beam $T_b/T_e \rightarrow 0$ has been made. The third term in (6) is a result of choosing a Maxwellian distribution for the electrons. By neglecting the third term, (6) can be solved for small n_b/n_0 using the weak beam approximation [Mikhailovskii, 1974]. Assuming $\omega_r = \omega_{pe} + \delta\omega$, one finds

$$\omega_r \approx \omega_{pe} \left(1 - \frac{1}{2\sqrt{2}} n_b/n_0^{1/3} \right) \quad (7)$$

Neglecting the fourth term in (6) instead of the third term, one finds the solution to the resulting equation is [Bohm and Gross, 1949]

$$\omega_r^2 \approx \omega_{pe}^2 (1 + 3(k\lambda_{De})^2) \quad (8)$$

The curve illustrated in Figure 8 for values of $V_b/V_i > 3$ results from a combination of effects illustrated by (7) and (8). For $2 < V_b/V_i < 4$, $k\lambda_{De}$ is slightly less than one, so the approximation used to obtain (8) is valid, resulting in $\omega_r > \omega_{pe}$. For $V_b/V_i > 4$, $k\lambda_{De}$ is much less than one, so the approximation used to obtain (7) is valid resulting in $\omega_r < \omega_{pe}$. If the beam density becomes a significant fraction of the plasma density, one can see that $\omega_r < \omega_{pe}$ could result. This case is not considered because the typical beam densities in the foreshock region are very small compared to the plasma densities.

The second limiting form of (5) is obtained by assuming $V_b/V_i \ll 1$. This limit is equivalent to the low phase velocity limit, $\omega_r/k \ll V_i$. For $\omega_r/k \ll V_i$ and $\omega_i \rightarrow 0$, $zZ(z) \approx 0$, so (5) is approximated by

$$D(k, \omega) = 0 \approx 1 + (k\lambda_{De})^2 - \frac{n_b/n_0 (k\lambda_{De})^2}{(k\lambda_{De} V_b/V_i - \omega/\omega_{pe})^2} \quad (9)$$

where the additional assumption of a cold beam, $T_b/T_e \rightarrow 0$, has been made. Solving this equation for ω_r one finds

$$\omega_r \approx \omega_{pe} k\lambda_{De} \left(V_b/V_i \pm \left(\frac{n_b/n_0}{1 + (k\lambda_{De})^2} \right)^{1/2} \right) \quad (10)$$

The general features of the curve in Figure 8 can be predicted using the approximations to the frequency of maximum growth in (7), (8), and (10). From (10) one can see that if $V_b/V_i \ll 1$ and $n_b/n_0 \ll 1$, then $\omega_r/\omega_{pe} \ll 1$ and from (8) one can see that if $V_b/V_i \approx 3$, then $\omega_r/\omega_{pe} \approx 1$. Thus the curve of ω_r/ω_{pe} versus V_b/V_i is predicted to vary smoothly from $\omega_r/\omega_{pe} \approx 0$ and $V_b/V_i \approx 0$ to $\omega_r/\omega_{pe} \approx 1$ and $V_b/V_i \approx 3$. From (7) one can see that if $V_b/V_i \gg 1$, then $\omega_r/\omega_{pe} \lesssim 1$. Thus the curve of

ω_r/ω_{pe} versus V_b/V_t is predicted to vary smoothly from $\omega_r/\omega_{pe} \gtrsim 1$ and $V_b/V_t \approx 3$ to $\omega_r/\omega_{pe} \lesssim 1$ and $V_b/V_t \gg 1$. The solutions in (7), (8), and (10) are only approximate and are not valid when $V_b/V_t \approx 1$. When $V_b/V_t \approx 1$, one must solve the full dispersion relation (equation (5)) numerically, as was done to obtain Figures 8 and 9.

COMPARISON OF THEORY TO OBSERVATIONS

In this section the observations of plasma oscillations summarized at the end of section 2 are compared to the predictions from the beam-plasma theory presented in section 3.

1. Plasma oscillations are observed at frequencies ranging from less than $0.1 f_{pe}$ to about $1.1 f_{pe}$. In Figure 8 the observed frequency range is reproduced by an electron beam that varies in velocity from $V_b/V_t \gg 1$ to $V_b/V_t \approx 1$. The time-of-flight mechanism causes the beam velocity variation. When the spacecraft is near the foreshock boundary, only high-velocity electrons reach the spacecraft, resulting in $V_b/V_t \gg 1$. Far downstream of the foreshock boundary, electrons with velocities on the order of the electron thermal velocity reach the spacecraft, resulting in $V_b/V_t \approx 1$. Thus the beam-plasma interaction and the time-of-flight mechanism combine to produce plasma oscillations in the observed frequency range.

2. As the plasma oscillations shift below the plasma frequency, their bandwidth increases from a few hundred hertz near the plasma frequency to ± 2 kHz well below the plasma frequency. This increase in bandwidth may be produced by a small fluctuation in the beam velocity. A small fluctuation in the beam velocity could occur in the foreshock region because of changes in the magnetic geometry. The effect of a small fluctuation in the beam velocity is understood by considering Figure 8. For $V_b/V_t > 4$, the curve of ω_r/ω_{pe} versus V_b/V_t has near-zero slope. For a small fluctuation in the beam velocity, plasma oscillations are generated over a narrow range of frequencies centered near the plasma frequency. For $V_b/V_t \approx 1$ the curve of ω_r/ω_{pe} versus V_b/V_t has a large positive slope. For a small fluctuation in the beam velocity, plasma oscillations are generated over a broad range of frequencies centered well below the plasma frequency.

The increase in the bandwidth as plasma oscillations shift below the plasma frequency may also be a consequence of the nature of the solutions of the dispersion relation. From Figure 8 it is concluded that when $V_b/V_t = 3$, plasma oscillations are narrow-band emissions near the plasma frequency because the growth rate versus frequency is sharply peaked near the plasma frequency. When $V_b/V_t = 1$, plasma oscillations may occur over a broad range of frequencies because the growth rate varies by a small amount over a broad range of frequencies centered well below the plasma frequency. Thus the change in bandwidth may be a consequence of the nature of the solutions to the dispersion relation or may be a result of a fluctuation in the beam velocity.

3. Plasma oscillations at the plasma frequency have wavelengths much greater than a Debye length. Plasma oscillations at frequencies well below the plasma frequency have wavelengths on the order of a few Debye lengths. The change in wavelength as plasma oscillations shift below the plasma frequency is illustrated in Figures 8 and 9. For $V_b/V_t \gg 1$, plasma oscillations occur near the plasma frequency and have long wavelengths ($k\lambda_{De} \ll 1$). As V_b/V_t decreases, plasma oscillations shift first above, then below the plasma frequency and the wavelengths shift from $\lambda \gg \lambda_{De}$ to $\lambda \approx \lambda_{De}$. One can understand why the wavelengths of plasma oscillations well below the plasma frequency are greater than the 30-m electric an-

tenna on ISEE 2 and less than the 215-m electric antenna on ISEE 1 by considering some typical plasma parameters for the foreshock region. If one considers a typical electron temperature and number density of 1.5×10^5 K and 9 cm^{-3} , respectively, then $\lambda_{De} = 9$ m. If $2\pi\lambda_{De}$ is used as the criteria for the minimum wavelength in the plasma, then $\lambda_{\min} = 56$ m. This minimum wavelength is greater than the length of the 30 meter electric antenna on ISEE 2 but less than the length of the 215-m antenna on ISEE 1. For $\lambda = 215$ m, $k\lambda_{De} = 0.23$. Referring to Figure 9, if $k\lambda_{De} = 0.23$, then for $V_b/V_t < 4$, the wavelengths of plasma oscillations are less than 215 m. When the spacecraft is located deep in the foreshock region, as in the example illustrated in Figure 3, $V_b/V_t < 4$ is satisfied, so the wavelengths are between 30 and 215 m. One can see that the observed wavelengths of plasma oscillations at and below the plasma frequency are predicted using the beam-plasma theory.

In addition to being able to predict the short wavelength below the plasma frequency, the observations of short wavelengths above the plasma frequency reported by *Etcheto and Faucheux* [1984] are also predicted using the beam plasma theory in the previous section. Etcheto and Faucheux reported observations of wavelengths between 130 and 215 m when ISEE 1 was a few R_E downstream of the foreshock boundary. Although they do not report a V_b/V_t ratio, one can see from Figure 8 that plasma oscillations above the plasma frequency occur for $2 \lesssim V_b/V_t \lesssim 5$. From Figure 9, $\lambda < 215$ m for $2 \lesssim V_b/V_t \lesssim 5$, thus both the short wavelengths above and below the plasma frequency can be accounted for using the beam plasma theory.

4. Plasma oscillations much below the plasma frequency are correlated with times when ISEE 1 is located deep in the foreshock region, far downstream of the foreshock boundary. This correlation can be understood by considering Figure 5. When ISEE 1 is located near the foreshock boundary (case 1), V_b/V_t is much greater than one, resulting in plasma oscillations at the plasma frequency. When ISEE 1 is located deep in the foreshock region (case 2), V_b/V_t is approximately equal to one, resulting in plasma oscillations well below the plasma frequency.

The critical velocity can be computed using the equation [*Filbert and Kellogg*, 1979]

$$V_c = D V_{sw}/\text{Diff} \quad (11)$$

where V_c is the critical velocity, D is the distance from the tangent point to the spacecraft, Diff is the distance from the spacecraft to the tangent field line along the solar wind velocity direction, and V_{sw} is the solar wind velocity.

As an example, consider the event illustrated in Figure 4. The critical velocity for this event varies from $V_c \approx 2 V_t$ at 1237:12 UT to $V_c \approx 0.8 V_t$ at 1240:28 UT. Unfortunately, due to large uncertainties in the position and shape of the bow shock and the fact that 64 s averages of the magnetic field were used, these values of V_c are only rough estimates. Using these rough estimates for V_c and the graph in Figure 8, one can predict that at 1237:12 UT plasma oscillations should occur near the plasma frequency and at 1240:28 UT plasma oscillations should occur well below the plasma frequency. From the middle panel in Figure 4 one can see that, as predicted, plasma oscillations occur at the plasma frequency as 1237:12 UT, and plasma oscillations occur well below the plasma frequency at 1240:28 UT.

A better estimate of the critical velocity is obtained from Figure 6. In Figure 6 distribution A the second peak in the reduced distribution occurs at $V_b \approx 9500$ km/s, or $V_b \approx 6 V_t$.

From this value of V_b/V_i and from the graph in Figure 8, plasma oscillations are predicted at the plasma frequency. As is seen in Figure 6, from 1237:51 to 1237:54 UT, plasma oscillations occur at the plasma frequency (~ 18 kHz). For Figure 6 distribution C, no peak is observed in the reduced distribution. However, the velocity where the distribution first deviates from the solar wind distribution may be taken as a lower limit on the critical velocity. As seen in distribution C, the lower limit is $V_c \approx 4000$ km/s, or $V_c \approx 2 V_i$. Using this value of V_c and the graph in Figure 8, plasma oscillations are predicted in the range of $0.8 f_{pe} < f < 1.0 f_{pe}$, depending on the beam temperature. Before comparing this prediction with the observations, the Doppler shift of the emissions must be considered. By using the value of $V_c \approx 2 V_i$ and the graph in Figure 9, the value of $k\lambda_{De}$ ranges from 0.4 to 0.6, depending on the beam temperature. By using $k\lambda_{De} = 0.5$ and $\lambda_{De} = 9$ m ≈ 100 m. The solar wind velocity was 500 km/s, so the maximum Doppler shift was approximately 5 kHz. In Figure 6 from 1238:27.6 to 1238:30.6 one can see that the bursts of plasma oscillations occur at varying frequency averaging about 5 kHz below the plasma frequency. Thus not only do the observations and predictions from the theory agree, this example verifies that the beam temperatures used in Figures 8 and 9 are reasonable estimates for the steep positive slopes of the beams that generate the plasma oscillations.

5. As the plasma oscillations shift below the plasma frequency, the flux of energetic electrons streaming from the bow shock increases at successively lower velocities. This correlation is interpreted as an indication that the time-of-flight mechanism discussed by Filbert and Kellogg is valid not only near the foreshock boundary, but is also valid far downstream of the foreshock boundary. Thus plasma oscillations throughout the foreshock region are generated by a beam-plasma interaction.

Although the above evidence supports generation of plasma oscillations by a beam-plasma interaction, the apparent evolution of the reduced distribution from a double-peaked distribution to a single-peaked distribution as the spacecraft penetrates into the foreshock region is inconsistent with the beam-plasma theory presented in section 3. In the context of linear plasma theory, the single-peaked distribution observed downstream of the foreshock boundary does not have a free energy source capable of driving electron plasma oscillations. The fact that plasma oscillations are observed downstream of the foreshock boundary indicates that a beam must be present in the reduced distribution. Using a model distribution for an event similar to the one illustrated in Figure 6, it was found that the Goddard Spaceflight Center electron spectrometer was capable of detecting a beam with any velocity, provided that the beam remained at a fixed velocity for the three seconds used to generate a reduced distribution. The observations of short duration bursts of plasma oscillations such as those illustrated in Figure 6 at 1238:20–1238:35 UT are an indication that downstream of the foreshock boundary, the generation of plasma oscillations occurs on much shorter time scales than 3 s. A typical burst lasts less than 50 ms and has a bandwidth of 5 kHz. As was pointed out above, a fluctuation in the beam velocity could account for the 5 kHz bandwidth of the bursts. Any 3-s time period may contain 20–40 bursts at varying frequencies. In the context of the beam-plasma theory in section 3, bursts of plasma oscillations at different frequencies are generated by bursts of electrons at different velocities. When averaged over 3 s, the bursts of electrons at different velocities would appear only as an enhancement in

the flux of upstreaming electrons. Further study of the wave and particle data is needed to confirm evidence that temporal variations of an electron beam are the reason why reduced distributions far downstream of the foreshock boundary do not appear to have regions of positive slope (i.e., a well-defined beam). It is possible that thermal fluctuations or nonlinear effects may be found which can generate these waves without a requirement for a region of positive slope in the reduced distribution function. However, at present the linear beam-plasma instability presented in this paper is believed to be the most likely generation mechanism because the predictions from this mechanism agree with the observed characteristics of plasma oscillations in the foreshock region.

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